Developing indoor heat-health warning systems for vulnerable populations

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With respect to the changing environmental conditions and extreme heat events associated with climate change, this article presents a review of existing heat-health warning systems[1] and discusses how such systems can be further augmented to account for indoor environmental conditions. The development of indoor heat-health warning systems is urgently needed to enhance the health and social care for vulnerable populations who spend long hours indoors. As a proof-of-principle study, we first introduce an indoor heat-health warning system developed for the general population in the UK, demonstrating its use case based on the 2013 heatwave event. Focusing on older people living in residential care — one of the most vulnerable populations worldwide — we illustrate the capabilities of an indoor heat-health warning system through a modelling framework which evaluates the impact of climate (change) on a building's heat and energy performance, from neighbourhood to city scales. An indoor heat-health warning system deployed at care homes should be able to foretell residents' indoor heat exposures given forecasts of impending heatwave events.

INTRODUCTION

Heat is a significant environmental and occupational health hazard, being the leading cause of weather-related deaths. Due to climate change, the number of people exposed to extreme heat is rapidly increasing worldwide. Between 2000 and 2019, about 489,000 heat-related deaths occurred each year.[2] For people over 65 years old, the mortality rate increased by about 85% between 2017-2021 compared to 2000-2004,[3] making this age group particularly vulnerable.

However, *"the negative health impacts of heat are predictable and largely preventable with specific public health actions. Action on climate change combined with comprehensive preparedness and risk management can save lives now and in the future"*[4] emphasizes the World Health Organization (WHO), highlighting the need for immediate action.

1 Heat health warning systems (HHWSs) are weather-(forecast)-based alert system designed to notify decision-makers and the public about upcoming heat events. They provide guidance on preventing heat-related health effects when forecasts predict that temperatures (and/or humidity) will reach or exceed thresholds at which significant health impacts are likely.

2 Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A. M., & others. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: A three-stage modelling study. The Lancet Planetary Health, 5(7), e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4.

3 Lancet Countdown. (2023). Heat-related mortality. Lancet Countdown Data Platform. https://www.lancetcountdown.org/data-platform/health-hazards-exposures-and-impacts/1-1-health-and-heat/1-1-5-heat-and-sentiment.

4 World Health Organization. (2024). Heat and health. Retrieved from https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health.

HEAT-RELATED HEALTH RISKS - WHO IS THE MOST VULNERABLE?

Due to climate change, many countries have been encountering an increased occurrence of extreme heat events. Even in countries with predominant heating needs like the UK, a new record-high temperature was recently observed in July 2022, surpassing 40°C. Consistent evidence indicates that human exposure to heat is directly linked to an increase in excess mortality and morbidity. Everyone faces health risks during a heat event, but a more thorough understanding of the contributing factors is essential to identify specific triggers for interventions aimed at reducing these potential risks.

Apart from the range of wider risk factors encompassing personal, environmental, and socio-economic elements, the causal pathways to heat-related illness and deaths clearly initiate with human exposure to heat. While this is a complex physical and physiological phenomenon in response to ambient environments, the human body utilises four main physiological mechanisms to keep itself cool: radiation through infrared rays, convection facilitated by water or air on the skin, conduction through contact with a cooler object, and evaporation of sweat. However, these thermoregulatory mechanisms can be impaired in specific populations and thus, certain factors increase their vulnerability[5]. These include older age, chronic illnesses (e.g., heart conditions, diabetes, respiratory or renal insufficiency, Parkinson's disease, severe mental illness), infancy, and an inability to adapt behaviour to stay cool (such as Alzheimer's, disabilities, and being bedbound).

> *"Indoor temperature is a more accurate predictor of heat exposure than outdoor temperature, especially for vulnerable populations whose cooling systems primarily depend on natural ventilation."*

These individual risk factors compound the susceptibility to heat-related health risks, often exacerbated by a lack of air conditioning, poor building thermal characteristics, and insufficient ventilation systems, especially *indoors* where those vulnerable individuals spend most of their time. For instance, according to an article published in 2022,[6] just 3 percent of homes in Germany and less than 5 percent of homes in France have air conditioning. In the UK, government estimates suggest that less than 5 percent of homes have mechanical cooling systems, such as air-conditioning (1%) and heat pump (1%), while 80% of households primarily rely on opening windows and doors to cool their homes.[7] Furthermore, within urban settings, the variation in local microclimate influenced by the urban heat island (UHI) effect[8] is critical, particularly at night when this effect is typically more prominent due to an increased sensitivity to heat exposure when sleeping.

It is well understood that studies have predicted a significant rise in human exposure to heat due to climate change, potentially resulting in an increase in mortality. However, indoor exposure to heat and the corresponding health outcomes have received relatively less attention. Several studies have evaluated indoor overheating and associated health risks in present and future climates. Notably, a field study affirmed that indoor temperature is a more accurate predictor of heat exposure than outdoor temperature, especially for vulnerable populations whose cooling systems primarily depend on natural ventilation.[9] This suggests that preventing heat-related health risks for vulnerable people requires a better understanding of occupants' *indoor* heat exposure during excessive heat events.

AN INTRODUCTION TO HEAT-HEALTH WARNING SYSTEMS

To address the challenges posed by climate change and associated extreme heat events, the World Health Organization's (WHO) Regional Office for Europe has developed Heat-Health Action Plans (HHAPs).[10] These plans aim to mitigate the negative health impacts of excessive heat. To do so, they utilise accurate and timely alert services such as meteorological early warning systems designed to analyse and identify weather- and climate-related risks and hazards. Additionally, they implement a health information strategy to provide valuable insights for medium and long-term development and urban planning.

5 UK Health Security Agency. (2024). Adverse Weather and Health Plan: Supporting evidence. https://assets.publishing.service.gov.uk/media/65fdb71af1d3a0001d32ae74/Adverse_Weather_and_Health_Plan_supporting_evidence__1_.pdf.

6 The Washington Post. (2022, July 20). Why European homes (usually) don't have air conditioning. https://www.washingtonpost.com/world/2022/07/20/europe-uk-air-conditioning-ac/.

7 Department for Business, Energy & Industrial Strategy. (2022). BEIS public attitudes tracker: Heat and energy in the home winter 2021. UK Government. https://assets.publishing.service.gov.uk/media/62960be8e90e070397a00faa/BEIS_PAT_Winter_2021_Heat_and_Energy_in_the_Home_REVISED.pdf.

8 The UHI effect is a phenomenon describing the elevated temperatures felt in towns and cities compared to rural surroundings and particularly felt at night-time as the heat retained by artificial surfaces is slowly released, keeping temperatures higher than in the countryside, combined with other impacts such as the reduced cooling effect of vegetation in urban areas, and the compounding effect of anthropogenic heat. (Royal Meteorological Society).

9 Zuurbier, M., Dons, E., Lanki, T., et al. (2021). Street temperature and building characteristics as determinants of indoor heat exposure. Science of The Total Environment, 766, 144376. https://doi.org/10.1016/j.scitotenv.2020.144376.

10 World Health Organization Regional Office for Europe. (2008). Heat-health action plans: Guidance. World Health Organization. https://www.who.int/publications/i/item/9789289071918.

For instance, Heat Health Warning Systems (HHWSs) are weather-based alerts designed to warn decision-makers and the public of impending extreme heat events and to advise them on preventable negative health outcomes. These systems assess the likelihood of exceeding of an 'action trigger', such as a threshold temperature at which there could be significant health impacts.

However, the metrics determining 'action triggers' for warnings are typically based on the correlation between outdoor weather conditions and reported critical outcomes, such as excess mortality and hospital admissions. Additionally, the spatial scale of these early warnings depends on the availability of local/regional weather forecasts. Therefore, the existing metrics may underestimate urban dwellers' exposure to heat, potentially leading to inadequate prevention of heat-related health risks. This is especially true for vulnerable populations in *indoor environments*, such as individuals aged 65 and older with existing health conditions and/or disabilities.

Indoor climates of buildings are determined by various factors such as the thermal characteristics of the building's envelope, its geometric configuration, internal heat loads resulting from occupants' activities, electric appliance usage, and the surrounding weather. These factors imply variations of indoor climates at room level. Taking these characteristics into consideration in Heat-Health Alerts services is crucial, especially for vulnerable populations that predominantly spend their time indoors. Moreover, this is particularly significant in regions like Europe and the Global South, where mechanical cooling measures are not widely adopted.

"Understanding the relationship between climate, buildings, and occupants is crucial for protecting and promoting the health and wellbeing of urban dwellers over time, as climate change projections evolve."

INDOOR HEAT-HEALTH WARNING SYSTEMS (CASE STUDY)

How can indoor heat-health warning systems (iHHWSs) be developed to account for building characteristics and urban microclimatic diversity? As a case study, we have performed a proof-of-principle study[11] of iHHWSs for urban dwellers in the city of Birmingham (UK).[12] In this study, we suggested combining the virtues of dynamic building energy simulations—a method to measure a building's energy performance—with an approach that can be practically applied to existing local Heat-Health Warning Systems (which action triggers are currently defined based on outdoor air temperatures). This combination provides a basis for a high-fidelity of indoor heat-health warning systems.

Two urban neighbourhoods were selected in Birmingham to highlight the largest differences in average recorded air temperature and the estimated Universal Thermal Climate Index (UTCI). The UTCI is a physiological heat balance model that considers the relationship between the human body and ambient environmental factors including air temperature, wind, radiation, and humidity. We compared these two neighbourhoods, which are the warmest and the coolest in the city. For this comparison, we referenced existing data on housing physical characteristics and internal heat load profiles based on occupancy. We identified five types of housing ($H_1 – H_5$), each with four types of insulation ($I_1 – I_4$), resulting in 20 reference housing combinations ($H_1I_1 – H_5I_4$), in each of the two neighbourhoods.

Based on these settings, we first estimated the effect of housing physical characteristics and urban microclimates on indoor heat stress among urban dwellers. We considered a heat index above 26.7°C, which indicates that fatigue is possible with prolonged exposure and that continuing activity could lead to heat cramps. This temperature can be used as an 'action trigger' for the new alert model.

Next, we investigated the relationship between outdoor temperatures and indoor heat stress to probabilistically identify outdoor temperature thresholds that affect indoor heat exposure at the urban neighbourhood scale. Finally, we compared our findings with the local (UK) heat-health alert service to illustrate potential indoor heat stress warnings and discussed the implications for long-term heat-health planning, particularly for vulnerable populations affected by heat.

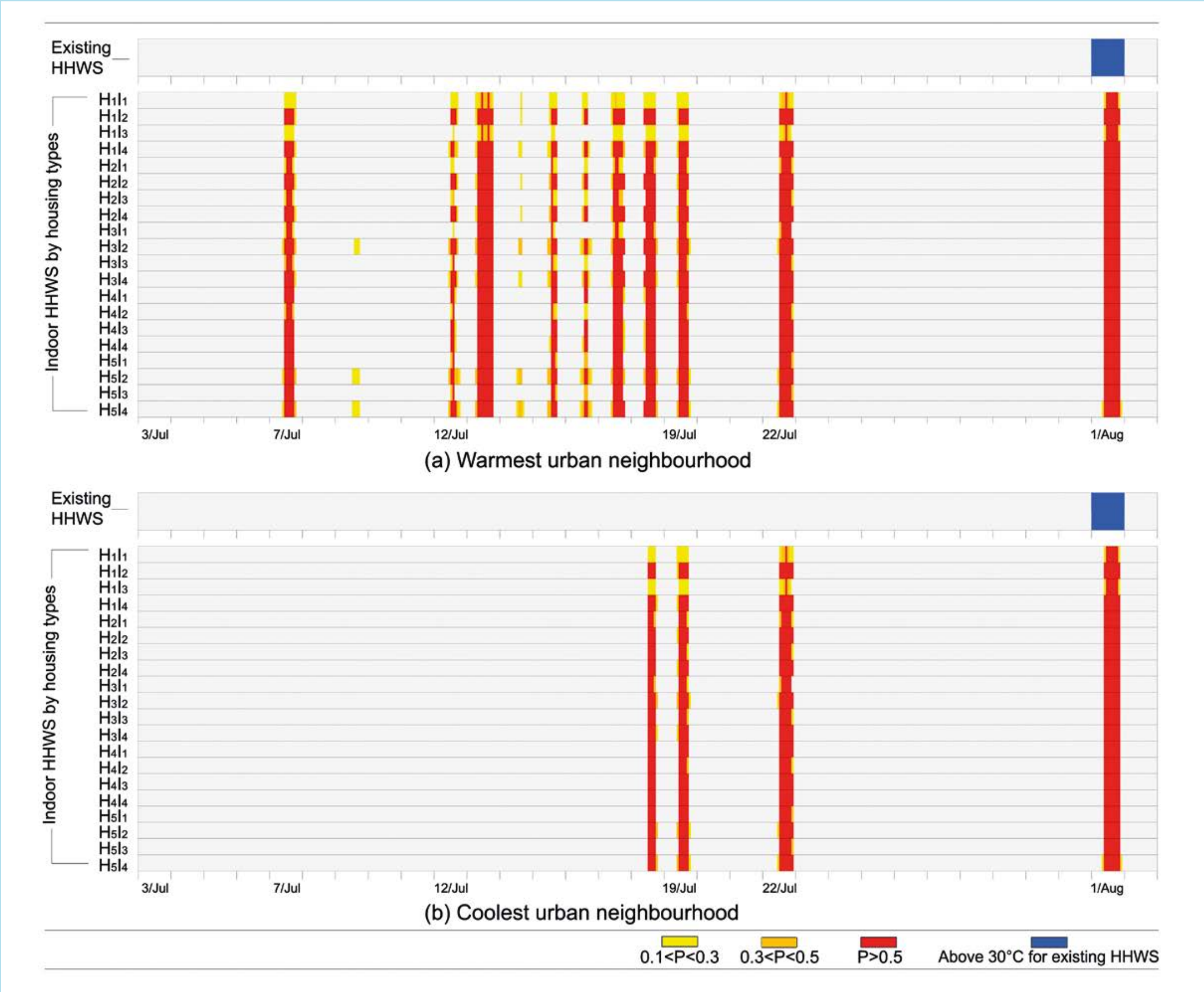
The results revealed significant variations in outdoor temperature thresholds affecting indoor heat stress across the 20 reference housing types locally. Based on these findings, we mapped probabilities-based indoor heat health warnings for each housing type and compared them to the existing local heat-health alerts ***(Figure 1)***.

Furthermore, for future years, we predicted the number of days when urban dwellings would experience indoor heat stress in the two neighbourhoods during summer (June 1st to Sep 15th, i.e., 107 days) based on projected daily maximum temperatures available at the local scale (e.g., UKCP18). To account for uncertainties in selecting the most appropriate climate change scenario for the local context, we used all available climate models (12 scenarios) to illustrate the overall trend of local heat exposure.

11 A proof-of-principle is a demonstration that aims to verify that certain theories have the potential for real-world application. Its purpose is to prove the feasibility of a theory, it is usually one of the first step of the development of an innovation/ process/theory. Here, our "proof of concept" is based on a study we carried out in 2023 in the UK

12 Yi, W., Liu, H., Zhang, L., et al. (2023). Modelling urban dwellers' indoor heat stress to enhance heat-health warning and planning. Building and Environment, 245, 110623. https://doi.org/10.1016/j.buildenv.2023.110623.

Figure 1: Comparison of potential indoor heat alerts between the warmest and coolest neighbourhoods of Birmingham relative to existing HHWS (2013)

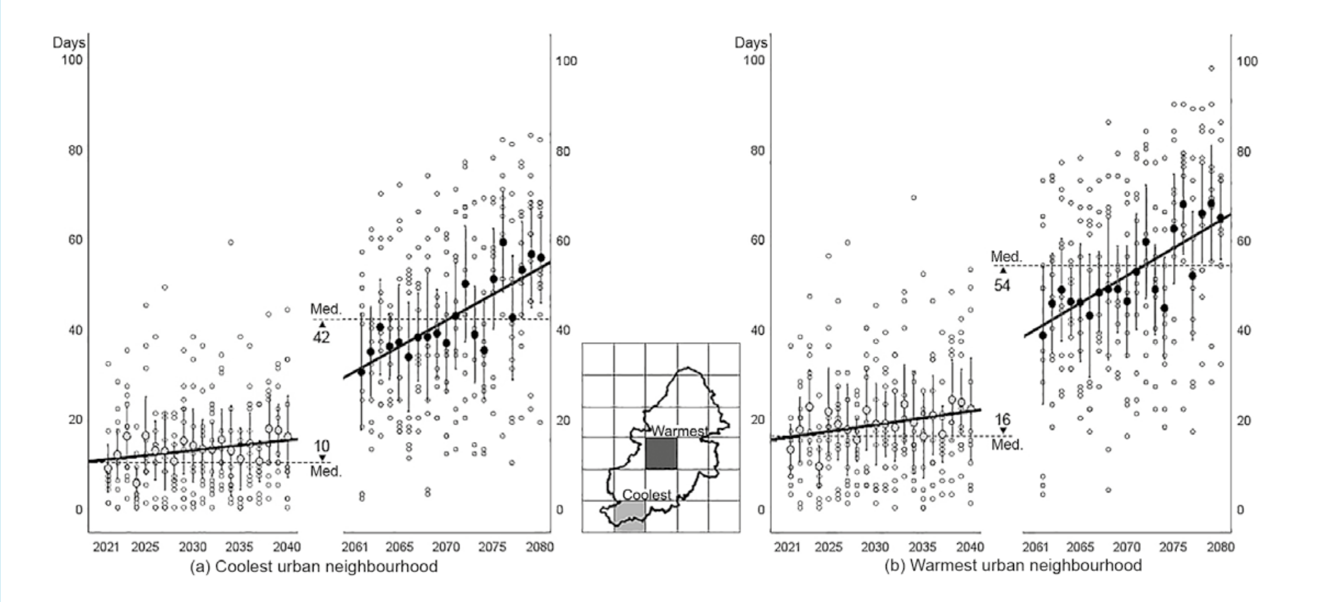


As part of short-term planning, a probability-based (colour-coded) Indoor Heat Health Warning System (iHHWS) was developed for the general populations of each housing type ($H_1l_1 – H_5l_4$) in Birmingham. This system was applied from July 3rd to August 2nd 2013, at the neighbourhood scale (warmest and coolest neighbourhoods). This approach was compared to the local Heat Health Warning System (HHWS), which issues alerts based on a 30°C daily maximum air temperature threshold during daytime. The figures above illustrate how the factors such as building characteristics and urban microclimate would have influenced the issuance of a HHWS alert. The colour-coded (yellow-amber-red) bars show the probability-based hourly occurrence of indoor heat stress (on the x-axis) when an alert should have been issued for each housing type (y-axis), while the blue square indicates the actual day the alert was issued.

Source: Yi et. al, 2023.

Finally, ***Figure 2*** proves that Heat-Health Planning needs to account for the urban dwellings' indoor heat stress at the local level, considering both medium- (2021-2040) and long-term (2061-2080) differences. It also shows that even within a single local climatic context, the diversity of urban dwellings' indoor exposure to heat stress at each housing level can be highly diverse. Understanding the relationship between climate, buildings, and occupants is crucial for protecting and promoting the health and wellbeing of urban dwellers over time, as climate change projections evolve. By enhancing heat-health planning, we can better assess and identify who is at risk, when, and where in both present and future climates. This will enable the development of effective, context-sensitive on-site environmental designs as adaptation or mitigation strategies.

Figure 2: **Comparison of projected indoor heat stress duration between the warmest and coolest neighbourhoods of Birmingham, mid- and long-term**



These graphs illustrate local differences in the predicted number of days urban dwellings will experience indoor heat stress ('caution' threshold set at >26.7°CHI) during the summer period (June 1st to September 15th) for the two selected local areas (the warmest and coolest urban neighbourhoods) in Birmingham, UK, in future years. They highlight that the disparity between cool and warm neighbourhoods is expected to widen in the future (with the difference in the median values of 6 to 12 days between neighbourhoods). This is due to temperatures projected to rise over the coming decades, with local variations expected.

Source: Yi et. al, 2023.

APPLICATION TO RESIDENTIAL CARE SETTINGS

This proof of concept demonstrates the feasibility of using building energy simulation techniques to assess indoor heat health across different scales, from neighbourhoods to entire cities. This approach could enhance the public health system's ability to respond to climate change. Further research is however necessary to address different clusters of population vulnerability.

"The likelihood of increasing cooling demand will be a significant challenge to net zero readiness in the future years. This requires renovating care homes resilient to climate change for balancing heat-health risk mitigation with minimising energy for space cooling."

Considering the heat-health factors noted earlier, particular attention can be given to people living in care homes. According to a census of the UK's care home residents,[13] approximately 82% of all care home residents in England and Wales were aged 65 years or older in 2021. Special consideration must be directed towards health conditions: only 18.7% of care home residents aged 65 years or older reported being in good or very good general health, while 31.8% reported being in bad or very bad health. Furthermore, among the older care home population, 70.9% were disabled, implying a lack of adaptive capacity to stay cool. Especially noteworthy is the average prevalence of people living with dementia in UK care homes, which stands at about 70%,[14] suggesting a limitation in their ability to communicate or express thermal discomfort.[15] Consequently, care homes saw a sharper rise in deaths (9.2% above the five-year average) during the heat events in 2022 ***(Figure 3)***.

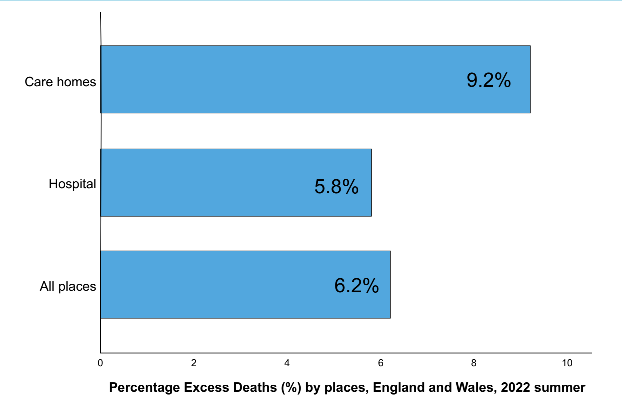
How to reduce risks for those living in residential care settings in response to climate change? WHO's general principles for Heat-Health Planning suggest adopting long-term strategies to mitigate climate change by adapting the built environment. This means that these strategies should

13 Office for National Statistics. (2023). Older people living in care homes in 2021 and changes since 2011. https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/ageing/articles/olderpeoplelivingincarehomesin2021andchangessince2011/2023-10-09.

14 Alzheimer's Society. (2019). Facts for the media about dementia. https://www.alzheimers.org.uk/about-us/news-and-media/facts-media.

15 Yi, W., Liu, H., Zhang, L., et al. (2022). Thermal comfort modelling of older people living in care homes: An evaluation of heat balance, adaptive comfort, and thermographic methods. Building and Environment, 207, 108550. https://doi.org/10.1016/j.buildenv.2021.108550.

***Figure 3:* Percentage excess deaths (%) by places, England and Wales, 2022 summer**



This graph presents the percentage of excess deaths (%) above the five-year average by places in England and Wales during the five heat-periods between June and August 2022, including days when a record-breaking temperature was reached.[16]

Source: Office for national statistics, 2022.

align with the global goal of achieving Net Zero CO_2 emissions by 2050, consistent with limiting global warming to 1.5°C above preindustrial level. Given the suggested modelling framework's capacity to identify which building types (and for whom) are at risk, specific interventions to provide optimal space cooling can be developed at the building and even room level.

For instance, keeping cool indoors can be a possible solution to reduce heat-related health risks. While passive cooling measures can be considered first, they may be limited in their ability to provide vulnerable populations with a safe and comfortable indoor environment in certain climatic contexts, such as hot and humid regions where mechanical cooling must be used. The likelihood of increasing cooling demand will be a significant challenge to net zero readiness in the future years. This requires renovating care homes resilient to climate change for balancing heat-health risk mitigation with minimising energy for space cooling. This is the focus of our research project "Renovating Care Homes Fit for the Future Balancing Indoor Heat Stress Risk Mitigation with Net Zero Ready by 2050",[17] funded by the AXA Research Fund.

While building energy simulation can inform context-sensitive strategies and renovation pathways for care homes fit for the future, it requires a finer spatial discretisation of local climate change projections. Once this work is completed, we would have a solid basis to evaluate the effectiveness of renovation measures in reducing this vulnerability through on-site adaptation.

CONCLUSION

In this article, we addressed the growing necessity for a robust framework to facilitate heat-health warning and urban planning efforts. It is crucial to demonstrate the variations in indoor heat-related health risks over the projected timeline of climate change. Our study reveals that outdoor weather conditions can predict distributions of local indoor heat stress in present and future climates. A further application of this approach to vulnerable populations living in care homes is needed, considering heat-health vulnerability factors.

This indoor consideration approach is becoming increasingly important due to an ageing society: 22% of the global population will be over 60 years by 2050, compared to 12% in 2015.[18] Globally, life expectancy[19] has increased by more than 6 years between 2000 and 2019, moving from 66.8 years to 73.4. Healthy life expectancy has also increased by 8% to attain 63.7 in 2019, implying that individuals may require clinical support or care from others from this age.

To respond to a rapid demographic shift as well as climate change, it is urgent to remodel care homes' indoor heat exposure at the city to regional scale. This will facilitate existing heat-health warnings and plannings. The project "Renovating Care Homes Fit for the Future" is currently carried out to balance heat stress mitigation with the goal of achieving net zero care homes by 2050. A better understanding of the relationship between climate, buildings and people will help protect and promote health and wellbeing of older populations living in residential care settings.

16 Office for National Statistics. (2022). Excess mortality during heat-periods: 1 June to 31 August 2022. https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/articles/excessmortalityduringheatperiods/englandandwales1juneto31august2022#excessdeaths-during-heat-periods-by-place-of-occurrence.

17 AXA Research Fund. (2023). Future-ready care homes: Reducing indoor heat stress while achieving net zero. https://axa-research.org/funded-projects/climateenvironment/future-ready-care-homes-reducing-indoor-heat-stress-while-achievingnet-zero.

18 World Health Organization. (2022). Ageing and health. https://www.who.int/news-room/fact-sheets/detail/ageing-and-health#:~:text=The%20pace%20of%20population%20ageing,from%2012%25%20to%2022%25.

19 World Health Organization. (2021). Global health estimates: Life expectancy and healthy life expectancy. World Health Organization. https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates/ghe-life-expectancy-and-healthy-life-expectancy.